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# EXPLORING THE BIOMECHANICS OF WALKING AND CROWD 'FLOW'

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## ABSTRACT

Crowd movement simulation models are generally based on aggregated speed and flow data collected more than 50 years ago. There appears to be no validated modelling capability to include the impact of recent and future changes in population demographics, resulting from an ageing population and increasing obesity rates. New analytical approaches and data gathering are required to successfully model crowd movement and safety for current and future generations.

This study carried out (a) a review of the primary components of crowd movement, demographics and analytical techniques (b) prototype experiments to investigate age-related aspects of space and potential points of contact and (c) a new predictive model for crowd flow analysis based on pedestrian biomechanics and anthropometric data. The model uses the physical space taken up by the biomechanical walking process and the spatial buffer between points of potential contact with other pedestrians to predict speed of movement at different levels of congestion.

The new analytical model was used to predict single file speeds (for people with different demographics in congested space) which compared well with published experimental data. The next steps for model development for wider 'flows' and additional experiments to provide data sets for wider demographics are also proposed.

## 1. INTRODUCTION

The existing models for crowd movement generally implement calculations which are based on average population flow data collected between 40 and 60 years ago, e.g.[1,2,3]. The use of long-established flow rate caps and uniform speed/flow/density relationships has been questioned by some of the original data collectors [4] who suggest that they may no longer reflect the population demographics of today. The "single-value" flow rate approaches may not account for the demographic trends predicted up to 2050 which suggest that global populations are expected to have a much greater proportion of elderly [5] and obese [6] pedestrians. There is a risk that continued use of generic analytical techniques and outdated data for design and computer modelling purposes will undermine the safety of future populations during evacuation from the built environment, as highlighted by Thompson et al.[7]. Therefore, a fundamental understanding of the process of walking in mixed ability populations is needed to inform the development of a more sophisticated, analytical model of pedestrian movement.

In order to address this problem, a systematic model development process was implemented, building on earlier work[8], comprising of the steps outlined below and is used as the structure for this paper:

(1) undertake a literature review to determine the core parameters of pedestrian movement and their inter-relationships;
(2) postulate a new model, capable of representing the dynamics of pedestrians of different ages, that uses pedestrian demographics and requires no formulae recalibration for different population groups or mixes of population types.
(3) conduct preliminary experiments on impact of age on model parameters
(4) test the model against previously published experiments;
(5) review and consider the next stages for model development

To minimise the number of variables to consider in the model, the initial focus was on single file flow. The potential to enhance the sophistication of the model with additional parameters and consider the expansion to model crowd flow in wider spaces is addressed in section 6.

## 2. LITERATURE REVIEW

The review and shortfalls in existing modelling approaches have been highlighted previously by Thompson et al.[7]. To more fully understand crowd flow for population groups with different demographics, the physical parameters of movement of individual people and how their locomotive movement is affected by (and will affect) others, need to be identified and quantified. As a starting point for new model development a comprehensive scoping review[9], using a methodological framework adapted from Arksey and O'Malley[10] was carried out to map the primary components of pedestrian movement and existing analytical approaches and models. This review was limited to uni-directional movement and crossed a number of disciplinary boundaries, i.e. clinical domains, psychology, social science, human biomechanics, computer science and fire engineering. The scoping review identified 50 parameters related to uni-directional movement and it highlighted the predominance of gait speed as a subject of investigation. Further analysis demonstrated 22 primary parameters which were related to gait speed, presented in Table 1.

| | | | |
|---|---|---|---|
| Age | Emotional state | Health status | Step frequency |
| Body projected area | Fatigue | Height | Step length |
| Bottlenecks, openings | Fitness | Lateral sway | Vision |
| Culture | Gender | Personal space | Weight |
| Occupant density | Group parameters | Social relations | Environment |
| Emergency or non-emergency | *Headway | Stair gradient | |

**Note: "headway" is often also referred to elsewhere as "inter-person distance".*

Table 1: Primary parameters for crowd flow identified in the scoping review

The results of the scoping review confirmed the complexity of the dynamics of crowd movement. During this initial phase of investigation, the aim was to develop a basic parametric model, where the number of "unknowns" were as limited as possible. Starting with the biomechanical determinants of gait speed, i.e. stride length and stride frequency, we considered how these parameters are manifested in a congested space. It is recognised that when moving in a crowd there may be a personal spatial restriction to stride length due to the limited space available for the leg swing of each person (to avoid physical collisions of toe/heel strikes). It is important, therefore, to understand the different components of walking in a congested space and their inter-relationships.

### 2.1 Components of pedestrian movement and movement in a congested space

When an individual is walking through the step-cycle, each foot-swing progresses forward, with the person's heel striking the floor with a regular cadence, as measured by Kitagawa et al.[11]. The measurement of distance between successive left and right heel strikes for floor contact is called the "*step length*", and the full-cycle (left-right-left) heel strikes is the "*stride length*", which is therefore double the step length. It should be noted that, in normal walking, at any single point in time the distance between left and right heel will never be as much as the measured step length because the heels are never simultaneously in contact with the floor unless the person is at a standstill[11, 12]. In this paper the *step extent* is defined as the longitudinal extent of the physical space taken by a person's walking motion, at any point in time, measured from the rearmost heel and foremost point of the foot. Note, the step extent is therefore just a proportion of the full step length+foot length at any point in the gait cycle, referred to later as factor *A*.

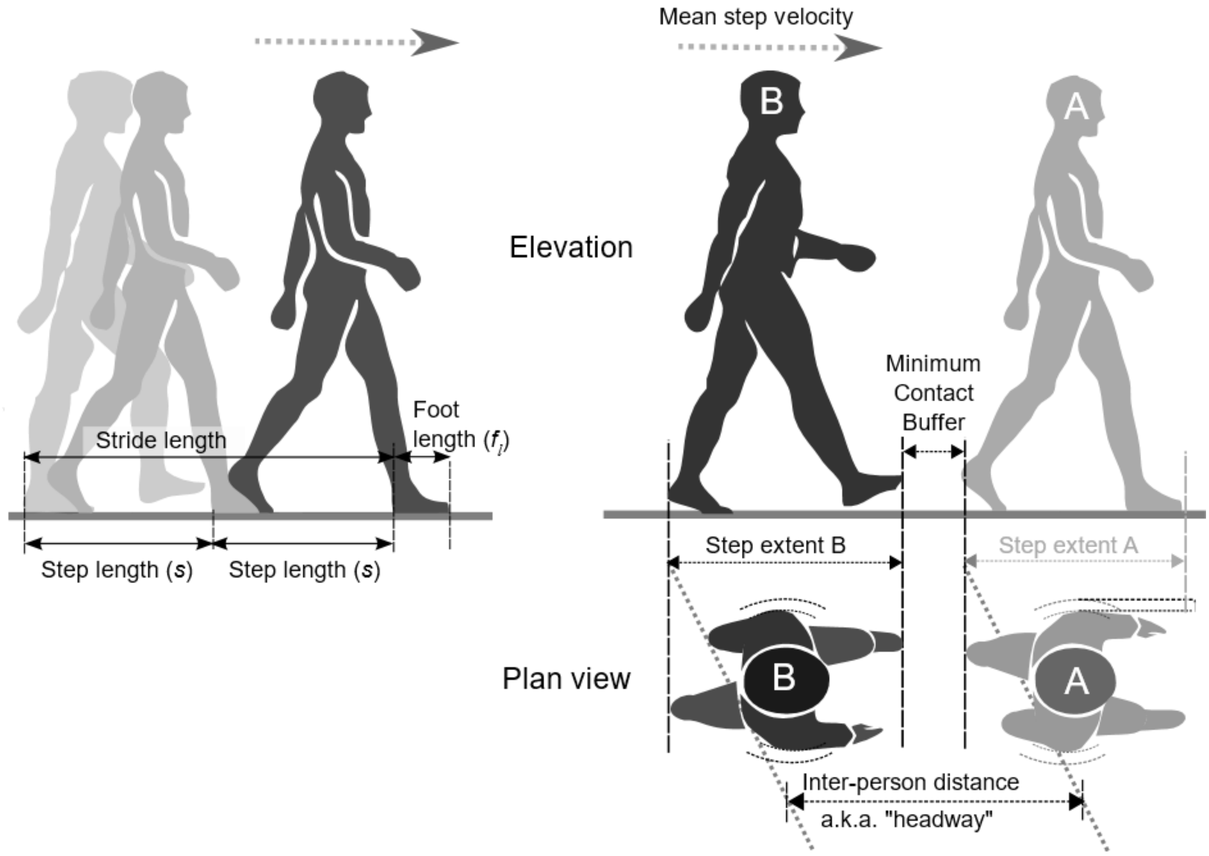



Figure 1: Components of pedestrian movement (left), and movement in congested space (right)

When a "Person B" walks behind "Person A" the space between the step extents of the two people is denoted as the "contact buffer" in Figure 1, which illustrates these components of walking and shows the "inter-person distance" (also known as "headway"). This denotes the total distance between the centres of Persons A and B.

These parameters form the basis of the proposed model and hence it is important to understand the inter-relationships between walking speed, step length, step extent, inter-person distance and contact buffer. The impact of lateral body sway and shoulder width are not considered at this stage. These lateral components will need to be considered later, primarily for wider congestion or movement through higher capacity doorways.

## 2.2 Relationship between walking speed and step length

The relationship between walking speed and step length of an individual has been studied by various researchers, both for free walking, where only one individual is studied and for congested situations. Cavagnia and Margaria[13] studied individual step length as part of the general mechanics of walking; Tanawongsuwan and Bobick[13] studied variations in individual step length at different speeds to investigate gait recognition in automated security analysis, whilst Dean[15] studied the relationship between step length and speed in order to quantify energy expenditure. Studies by Jelic[16] and Wang et al[17] quantified step length and speed in congested conditions. While the experimental contexts and ranges of walking speeds varied, the same basic trend was observed, i.e. step length was shown to reduce as walking speed is reduced. Another consistent observation was the wide variation in individual step lengths for a given walking speed.

The relationships between step length and walking speed as derived from each of the studies are illustrated in Figure 2. Studies did not investigate the variation in step length across the same range of speeds. Tanawongsuwan and Bobick[14], Cavagna and Magaria[13], Dominici[18] and Jelic[16] each demonstrated a linear relationship between step length and walking speed. However, with the exception of the latter, the step length was only determined for speeds greater than approximately 0.7 m/s. Seitz et al.[19] studied linear step length variation at or above preferred walking speed in uncongested flow, but used fixed step length values in a movement model to assess points of change in direction.

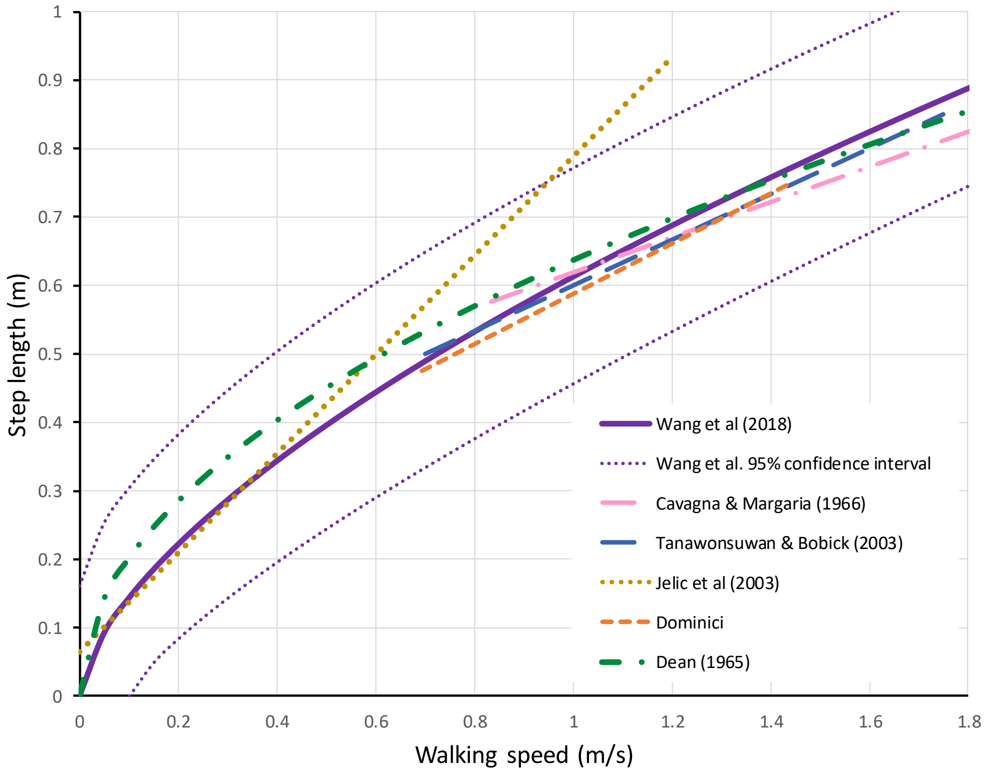



Figure 2. Step Length vs Speed from selected experimental analyses

Both studies by Dean [15] and Wang et al [17]. included sampling over a wide range of speeds, from near standstill up to “faster than normal” pace, and ascertained that a better fit was achieved by using a simple ‘power’ relationship, presented in Equation 1.

$$s/\tilde{h} = cv^n \qquad [1]$$

where: $s/\tilde{h}$ is “step length”, normalised proportionally for a statistical average height $\tilde{h}$ of 1.72m,
$v$ is walking speed,
$c$ and $n$ are constants derived from statistical fit calibrations
(c=0.637, n=0.5 for Dean[15] and c=0.613, n=0.631 for Wang et al[17]).

The statistical normalisation of the step length reduced the variance in the results, making the trends more apparent. This step length normalisation essentially adjusts the experimental sampling to an equivalent population cohort with a uniform height of 1.72m and similar ‘free’ walking step length. Therefore, the slightly tighter band of confidence interval shown for Wang et al in Figure 2 was achieved.

The statistical approaches by Dean and Wang et al. are similar, and the curves are relatively similar, taking into account the spread of data (shown by the confidence intervals). Note that Dean’s study is for an individual walking in uncongested experimental conditions whilst Wang et al’s study was in congested conditions. The similarities in the derived curves may indicate that the reduction in step length with reduction in speed is predominantly a natural biomechanical process, rather than a product of crowd congestion itself.

### 2.3 Considering the possible determinants of the contact buffer

As indicated in Figure 1, we have termed the space between the step extents of two people the “contact buffer” and it is also important to understand the relationship between the contact buffer and speed. We can leverage a useful analogy here from traffic flow since both pedestrian and road traffic flow involve people responding to the movement of other people in front and adjusting their speed and position accordingly[20]. In traffic flow it is widely accepted that there is a defined “reaction/response” time assessed between vehicles to enable drivers to respond to changes in position of vehicles in front. At different speeds, these times translate to different distances between one vehicle and the vehicle in front.

The flow dynamics literature has identified an equivalent concept, termed the “adaption time’ [22] (or safe response time). This refers to the time that is required for a person to react and adjust their walking speed or completely stop with the purpose to avoid collision. It is important to note that, in the context of people movement the distance that individuals leave may not only be related to the time that they perceive is needed to avoid collision at a particular speed, but also related to the goal of preserving personal space.

The Handbook of Road Technology[20] suggests that drivers in road traffic leave a timed buffer between their own car and the car in front, with a base response time of 0.25 seconds. It also suggests an additional adjustment of 0.2 seconds to allow for additional response time needed for elderly drivers. The need for this age-related adjustment is reflected in a large body of research on reaction times. For example, Woods et al[23]) in their experiments on simple reaction time observed this time increasing linearly with age. The authors reported that, at age 18, the mean simple reaction time was 218ms, and at age 65 it was 239ms.

In both traffic flow and crowd flow we are considering the ability of people to move and respond to changes in position of potential ‘obstructions. Notwithstanding that the speed ranges and other aspects of response in traffic flow (e.g. the act of physically pressing on a brake pedal) are different from that experienced in crowd flow, we can conclude that the contact buffer, Figure 1 is likely to vary with speed and age.

## 3. DEVELOPMENT OF A NEW MODEL FOR CONGESTED MOVEMENT

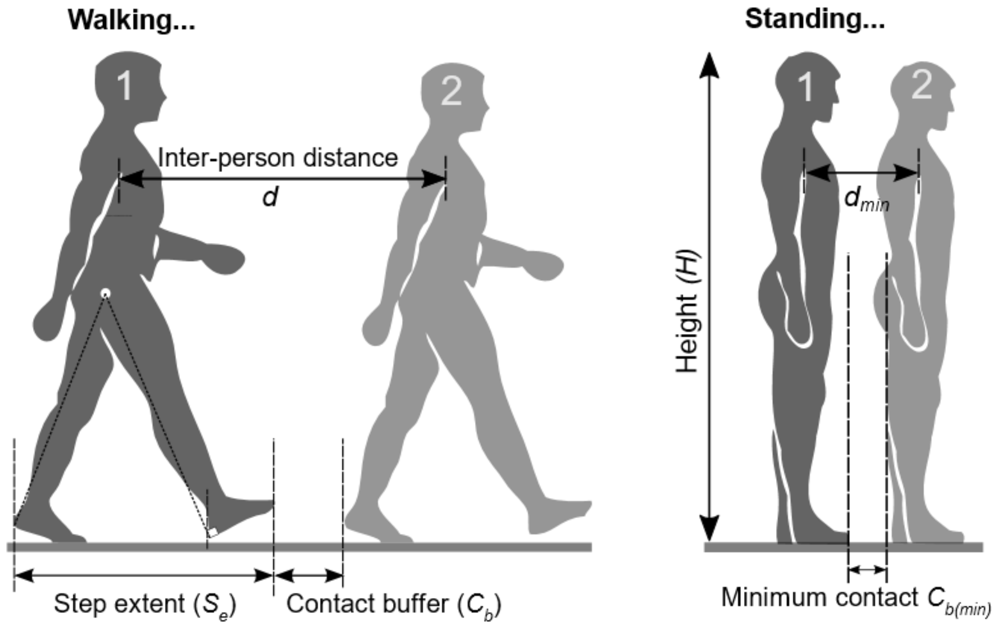
The development of the mathematical model began by referring to the parameters listed in Table 1, having an understanding of the basic parameters of movement and some understanding of their interrelationships. The overall aim is to develop an emergent model of movement (termed the “movement adaption model”) which reflects the inter-relationship between speed and inter-person distance, i.e. the model assumes the need to consider the walking movement of each occupant, in conjunction with the desire to avoid colliding with other people and the physical and cognitive ability to do so. The basic parameters that were initially considered as components of a new single-file model are:

1. Unimpeded normal walking speed (which will be affected by age, fitness, gender, height).
2. Body dimensions (such as height, and related leg length and foot length).
3. Gait parameters (step length, step frequency, manifested as instantaneous walking speed).
4. Contact adaption time, the time required for a person to react and adjust their walking speed or completely stop with the purpose to avoid collision (this may be affected by age and vision)
5. Minimum Contact Buffer (minimum distance from bodily extent to potential physical contact with an obstructing person) as shown in Figure 1.

The "movement adaption model" aims to quantify these components and considers how the dynamic elements change in relation to each other in order to produce the emergent, inter-related, properties of occupant density, inter-person distance (or headway) and collective speed. If the walking movement for individuals with different characteristics (such as age etc.) can be mathematically described, and if how their movement changes as congestion increases can be understood, then it would be possible to plot graphs to compare the overall crowd flow and speed for different demographic types. It is crucial that, as the new model is developed, it should be cross-referenced not only to different population demographics, but also compared with the established data which consider changes to crowd speed and flow at different levels of congestion (crowd density). We do not use any of the analytical components described in the Optimal Steps model described by Seitz et al.[19] because that model actually used a derivation of the social force model[21] to calculate speed, calibrated with established speed/density diagrams (for an aggregated population), and the step length in the model itself did not vary with speed.

### 3.1 Defining the components of inter-person distance, d.

Figure 3 illustrates that the inter-person distance comprises a proportion of the step length plus the foot length (i.e. the step extent) plus the contact buffer.




(a) (b)

Figure 3. Linear, geometric components of two people walking (a) and standing in single file (b).

Therefore, for full, unrestricted walking speed, the inter-person distance for 2 people identified in Figure 3 as person[1] and person[2] is given by the sum of the step extent $S_e$ and the contact buffer, expressed in Equation 2a:

$$d_t = A\left(\frac{s_{u[1]}+s_{u[2]}}{2} + f_{l[1]}\right) + C_b \qquad [2a]$$

If both people have the same demographics, this simplifies to:

$$d_t = A\,(s_u + f_l) + C_b \qquad [2b]$$

where, in the above equations, and Figure 3:

$d_t$ = threshold inter-person distance between centroid of Person 1 and centroid of Person 2 (m),

$A$ = factor for step extent, as a proportion of step length + foot length (explained in section 3.3)
$s_u$ = step length for people of equal demographics (m)
$s_{u[n]}$ = unimpeded step length (m) for person[n] (m)
$f_l$ = foot length for people of equal demographics (m)
$f_{l[n]}$ = foot length of person n, allowing for footwear
$C_b$ = contact buffer (m)
$C_{b(min)}$ = minimum contact buffer, at stand-still with minimum inter-person distance $d_{min}$ (m)

### 3.2 Deriving the relationship between step length and walking speed

As noted previously, the relationship between walking speed and step length of an individual has been studied by various researchers. Whilst all confirmed the same trend, i.e. a reduction in step length with walking speed, some[13,16] established a linear relationship whilst others[17,17]) suggested a power relationship (equation 1). In the absence of an agreed relationship, a power relationship of the form proposed by Dean[15] and Wang et al[17] (Equation 1) is proposed in this initial stage of model development for two reasons. Firstly, these studies considered the relationship over a wider range of speeds, particularly in the lower speed ranges. It is apparent that walking is still progressive at these lower speed ranges and therefore needs to be considered. Secondly, it may be unrealistic to project the linear relationships determined in other studies beyond the range of speeds for which they were collected, especially because that extrapolation sometimes indicates a substantial step length at zero speed.

In order to assess the relationship between walking speed and step length for different population groups, it should be possible to incorporate basic group demographics, which affect step length and walking speed into Equation 1. Data are readily available for the height and normal, unimpeded walking speeds of different population groups, so it may be possible to combine the unimpeded movement parameters with the same form as that in equation 1, to derive equations 3 and 4.

$$\frac{s}{s_u} = C\left(\frac{v}{v_u}\right)^N \quad [3]$$

$$\therefore\ s = C.s_u\left(\frac{v}{v_u}\right)^N \quad [4]$$

where: $s$ = step length, $s_u$=unimpeded 'normal' step length, $v$=walking speed, $v_u$=unimpeded walking speed (m/s), $C$ and $N$ are constants. Note these constants are not assumed to be the same values as those for $c$ and $n$ in Equation 1 since here we are expressing the step length and speed as proportions relative to the unimpeded values, in order to relate them to established, standard, demographic parameters.

It is also important to recognise that the full unimpeded step length $s_u$ is a function of a person's height and so the unimpeded step length $s_u$ can be expressed in Equation 5.

$$s_u = h.F \quad [5]$$

where $s_u$=unimpeded 'normal' step length, $h$ = person height, F=ratio of step length to height.

Note that Hatano[24] identified that on average for adult males F=0.415, for adult females F=0.413 and, therefore, 0.414 might be used for an evenly mixed statistical averaged group of males and females, if we also only know an average height for the group.

We can therefore combine equations 4 and 5, substituting for $s_u$:

$$s = C.h.F\left(\frac{v}{v_u}\right)^N \quad [6]$$

For the purposes of the model it was important to explore the value of C in Equation 6. Previous data identified for the purposes of exploring this value were the average group speeds and demographics of participants in the experiment conducted by Cao et al[22]. This experiment was of interest since it considered both young students and elderly walking around a circuit, at different speeds (incurred by occupant density) where the height and unimpeded walking speeds of the subjects were measured before the experiments were undertaken. We tested Equation 6 with Cao's reported values for young (mean height, $h$=1.64 m, and unimpeded walking speed, $v_u$ = 1.23 m/s) and old ($h$=1.62 m and $v_u$ =0.95 m/s) with $F$=0.414, and with the power factor N = 0.631(from Wang et al [17])). In the first instance we set a default value of C = 1. A comparison of Equation 6 for young and old cohorts with the relationships established by Wang et al[17] is presented in Figure 4.

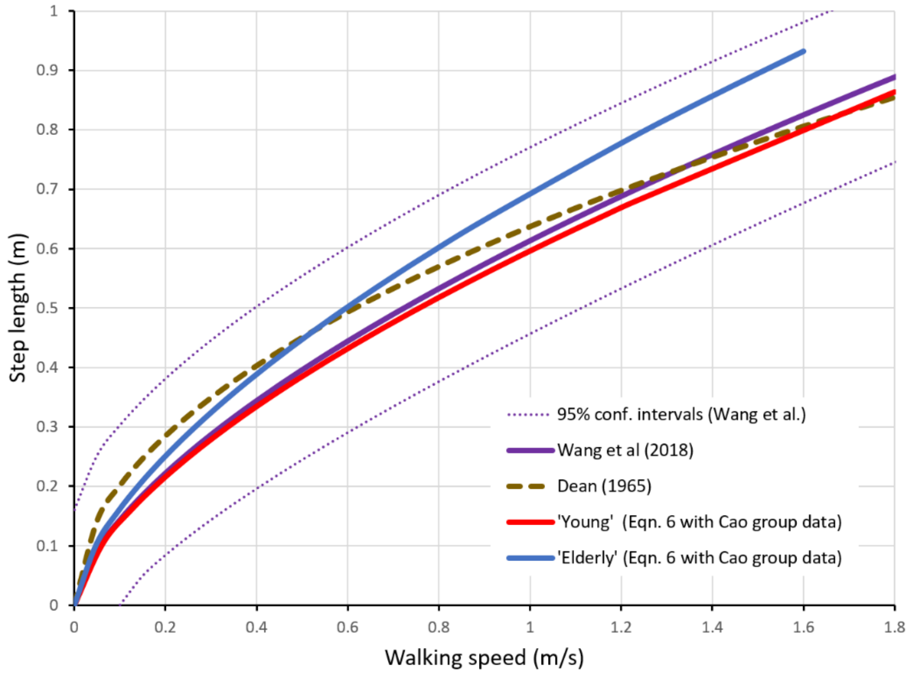



Figure 4. Walking speed vs step length, comparing "movement adaption" model to published data.

Figure 4 illustrates that the relationship between step length and walking speed as expressed in Equation (6) with a default value C=1 aligns very closely with the height-adjusted younger students in the Wang et al.[17]. Note that 'Young' and 'Elderly' plots were plotted with Equation 6 (using demographics data from the two groups collated by Cao et al with the average values of $v_u$ and $h$ collected for the experiments). The young and elderly were observed walking up to approximately 1.8 and 1.6m/s respectively in the experiments, so our curves are projected only up to those limits.

If we additionally normalise the step length in relation to the height for the "young" cohort we see a near exact overlap when plotted against the Wang et al. curve. For the initial stage of the model, we therefore simplify equation 6, by substituting C=1 into equation 7 thus:

$$s = s_u \left(\frac{v}{v_u}\right)^{0.631} = h.F\left(\frac{v}{v_u}\right)^{0.631} \qquad [7]$$

where: all terms referenced in equations 4 and 5 apply, $C$ is removed and N= 0.631 (from Wang et al [17])

### 3.3 Derivation of the maximum Step Extent, $S_e$ (as proportion of step & foot length)

The linear, geometric components of two people walking, and standing in single file is illustrated in Figure 3. The step length and foot length are both components of the step extent. However, as noted previously, the step extent during a gait cycle is always less than this maximum distance between the rear heel and front toe since both heels are never in contact with the floor at the same time in normal walking. It has also been noticed by other researchers (Seyfried et al[25])that the process of people walking behind each other "*…is achieved by some persons setting their feet far right and left of the line of movement, giving some overlap in the space occupied with the pedestrian in front*". Therefore, it is clear that only a proportion of the full walking step length and foot, termed the *step extent,* should be applied over the duration of the walking cycle.

The *step extent* at any point in time represents the length of physical space occupied by a walking person. It is therefore important in the model to relate this to the sum of step length plus foot length, by determining the value of A, presented earlier in Equation 2. An on-screen analysis of the publicly available videos from the study of Tanawongsuwan and Bobick[14] was conducted to assess the step extent, $S_e$, of a test subject over one gait cycle at normal walking speed. The study was chosen because it was in controlled, overground conditions, from a precise "side-on" view, which made analysis more accurate. Although the measurement accuracy was limited by the number of screen pixels, an initial approximation for both the average step extent and the maximum step extent as a proportion of the total 'foot length + step length' was possible in order to estimate the physical space occupied by the walking person. The results are illustrated in Figure 5, which shows that the Step Extent (at any instant) will always be less than the sum of Step Length($s$) + Foot Length($f_l$). The magnitude of the step extent varies during the step cycle, from a peak at full extent (92% of $s + f_l$) to when the left and right feet pass each-other mid cycle (~27% of $s + f_l$). Although there appeared to be a moderate increase in these proportions with reduced walking speed, insufficient data points were available to draw a statistically meaningful trend. Therefore, the value of $A = 0.92$, was used to convert "foot and step length" to peak Step Extent.

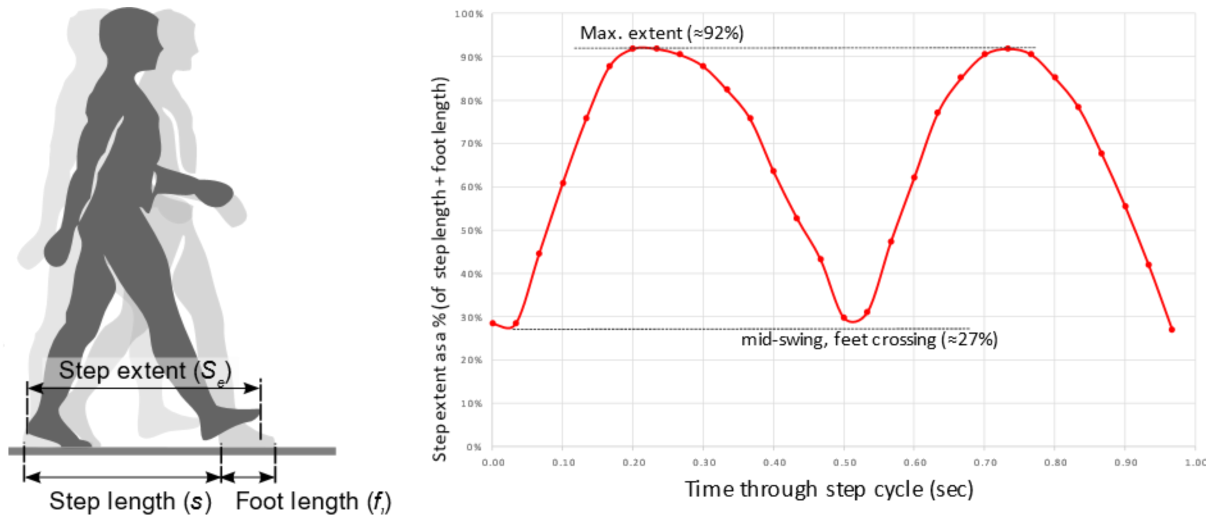



Figure 5: Step Extent $S_e$, as a percentage of (Step Length + Foot Length) during one step cycle.

### 3.4. Understanding the Contact Buffer, $C_b$

As noted previously the inter-person distance, $d$, comprises the sum of the maximum step extent (representing the physical space occupied by a walking person) and the contact buffer $C_b$. It is postulated that the contact buffer in Figure 3 is the distance (of Person 1) away from anticipated potential points of contact (with Person 2). This contact buffer has a minimum value, representing comfortable "personal space" e.g. when queuing at stand-still, but is also related to "adaption time" when walking forward to allow for basic detection and response to possible changes in movement of the person ahead. The minimum contact buffer and walking contact buffer calculations are proposed in Sections 3.4.1 and 3.4.2.

### 3.4.1 The minimum contact buffer

The minimum contact distance (at maximum crowd density when the crowd is at zero speed or "standstill") represents their minimum "personal space" (Figure 3b) and may be affected by several factors such as stress, culture or situation. This minimum contact buffer is related to the density thus:

$$C_{b\,(min)} \; = d_{min} - b \qquad [8]$$

where: $C_{b(min)}$ = minimum contact buffer (m), $d_{min}$ = minimum inter-person distance (m), b is body depth, i.e. the horizontal extent of the body, evaluated as the larger of the torso depth or foot length (m).

Also, the minimum inter-person distance is equal to the inverse of the maximum single file density, $\rho_{max}$ (persons/m), thus:

$$C_{b\,(min)} \; = \frac{1}{\rho_{max}} - b \qquad [9]$$

### 3.4.2 The contact buffer, when walking forward.

The distance left by an individual to account for the 'contact adaption time' represents the time to detect and potentially respond to a change in movement to the person in front, to avoid contact. This is analogous to the distance that a driver might leave between his vehicle and the vehicle in front and may be expected to vary depending on speed. It is expected that the movement "detection" time would be related to visual response time, and the contact adaption time may require additional adjustment to stop if the person behind was less mobile than the person in front.

The contact buffer, for non-zero walking speeds, is expressed as the distance derived from the contact adaption time, but only for values above the minimum contact buffer:

$$C_b \; = (v \times T_a) \qquad \text{for} \qquad C_b \geq C_{b\,(min)} \qquad [10]$$

Where: $C_b$ = Contact buffer(m), $C_{b(min)}$ = minimum contact buffer, $v$ = current walking speed of individual, $T_a$ = contact adaption time.

Note that the contact adaption time may be affected by age, culture and potentially other parameters, and also $C_{b(min)}$ is expected to vary with conditions and may tend to diminish as frequent contact is likely to occur in 'high-activity' ('stressed') crowds.

## 3.5 The overall movement adaption model

The relationship between inter-person distance, $d$, the maximum step extent, $S_e$ (as a proportion (A) of step length ($s$) plus foot length ($f_l$)) and the contact buffer, $C_b$ for full, unrestricted walking speed for two identical persons was given in Equations 2a and 2b. The *threshold inter-person distance* $D_t$, i.e. the smallest distance that will just allow a person behind to walk at full normal walking speed without impediment, can be calculated with Equation 2b, using the person's demographics parameters and normal, unimpeded walking speed. For analyses above the threshold distance, then it is assumed that Person 1 will adopt a normal unimpeded walking speed, in calm, non-stressed conditions according to:

$$v = v_u \quad \text{when} \quad d >= D_t, \qquad [11]$$

where $d$ is inter-person distance (centroid to centroid) and $V$ is walking speed.

For proximities below the threshold distance, the step length, s, reduces with the space available, in relation to the reduced walking speed. Equation 2a can then be combined with the underlying equations 7 (for step length) and 8 and 9 (contact buffer) resulting in an equation which relates inter-person distance to biomechanics factors for uniform population groups (Equation 12a). This equation is modified at very low speeds, where the contact adaption time multiplied by the speed is less than the minimum contact buffer.

*Sum of linear distance components*

*Max. step extent* | *Contact buffer*

*Step* | *Foot*

*Walking with contact buffer above the minimum: where* $C_{b(min)} < v \times T_a$

$$d = A\left( s_u \left(\frac{v}{v_u}\right)^{0.631} + f_l \right) + (v \times T_a) \qquad [12a]$$

*At standstill or low speeds where contact buffer determines personal space*: $C_{b(min)} >= v \times T_a$

$$d = A\left( s_u \left(\frac{v}{v_u}\right)^{0.631} + f_l \right) + C_{b(min)} \qquad [12b]$$

Summarizing all terms:

- $v$ = walking speed (m/s)
- $d$ = inter-person distance, at a given speed(m)
- $A$ = step extent factor =0.92
- $f_l$ = foot length allowing for footwear(m),
- $v_u$ = unimpeded walking speed(m/s),
- $s_u$ = unimpeded step length(m),
- $T_a$ = contact adaption time (s)
- $C_{b(min)}$ = minimum contact buffer(m)

The model thus developed and expressed in Equation 12 is called the "movement adaption model".

## 4. EXPERIMENTAL INVESTIGATION OF AGE RELATED DIFERENCES IN CONTACT BUFFER

There is one term in the model for which there was no reference data available for walking in crowds, namely the contact adaption time $T_a$. In our discussion of contact adaption time using the traffic analogy in section 2.6 above, we concluded that reaction to a stimulus and the time taken to produce a required movement is age dependent. In pedestrian traffic, reduced sensori-motor functioning at many levels of the nervous system is likely to affect how older adults choose to position themselves with respect to a person ahead of them on their path. There is a paucity of research quantifying contact adaption time or indeed how this might vary for different demographics. In order to develop an estimate for the relative differences in contact adaption time for different demographics, a basic study of individual movement was conducted to investigate the difference between the distance that young and older adults chose to leave between themselves and a "person-shaped" object while walking on a treadmill. This proof-of-concept study set out to investigate the relative impact of increases/decreases in speed on the 'contact buffer' relative to the 'person' in front. The following hypotheses were tested: 1) the contact buffer for older adults would be greater than for younger adults for a given speed; 2) the contact buffer would vary with speed.

### 4.1 Experimental Methods and participants

The sample was comprised of 9 young adults, aged 19-34 (mean age 24.4) and 13 older adults aged 60-84 (mean age 67.8). A breakdown of the anthropometric data of the sample is given in Table 3. Ethical approval for this study was granted by Ulster University Research Governance Filter Committee. All participants were screened and taken through an informed consent process.

The experimental set-up is shown in Figures 6 and 7. An adult-sized flat mannequin was placed at the front of the treadmill above the motorized belt. This ‘person-shaped’ object was intended to emulate an evacuating person moving at the same speed as the evacuating occupant in a scenario where overtaking is not possible. Participants’ movement was captured using the Qualisys Miqus optical motion capture system. Six 3D motion capture cameras were located around the treadmill, 3 each side, mounted to tripods and connected in series to the laptop containing visual 3D software.

Table 2. Demographic data for laboratory study

| Group | Male no. | Female no. | Age | | Height (cm) | | Leg Length (cm) | | Weight (kg) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Min-Max | Mean *(s.d.)* | Min-Max | Mean *(s.d.)* | Min-Max | Mean *(s.d.)* | Min-Max | Mean *(s.d.)* |
| Young Adult | 4 | 5 | 19 - 34 | 24.44 *(4.42)* | 166 - 186 | 171.33 *(12.12)* | 81 - 99 | 88.33 *(5.63)* | 61.9 - 100.0 | 77.34 *(14.25)* |
| Older Adult | 6 | 7 | 60 - 84 | 67.77 *(8.62)* | 152 - 178 | 167.15 *(7.83)* | 79 - 97 | 88.33 *(5.63)* | 59.9 - 104.1 | 77.43 *(11.40)* |

Figure 6. Experimental Rig

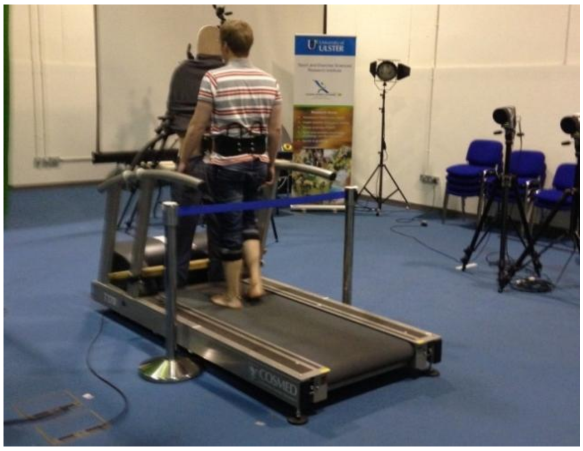


Figure 7. Rig showing participant and barrier

Each participant was instrumented with markers on the first metatarsal head (distance from end of toe to toe marker was approximated to be 0.045m across all subjects), lateral malleolous, and achilles tendon at the same height as the lateral malleolus (see Figure 8). A cluster plate which contained four markers attached to a shell, was located on the lower rear back of the flat mannequin. The contact buffer defined previously was calculated in this experimental set-up by measuring the minimal distance between the toe and the static mannequin.

Figure. 8. Marker Locations

There were two experimental conditions: walking on the treadmill unconstrained and walking on the treadmill with the addition of a belt barrier at 0.82m from the ‘man-shaped’ flat mannequin (see Figure 6). This distance to the belt barrier was approximately half the treadmill length, in order to create an understanding of movement in a more restricted space. Note that the participants' gait was not actually physically hampered by the barrier as the leg was free to extend backwards. Within these two conditions, participants were asked to walk at 3 different speeds. Demographic (age, gender) and anthropometric data (height, weight, leg length) were recorded for each subject. Leg length was measured using a tape measure from bony landmarks, namely the ASIS and the medial malleolus. Each participant was asked to step onto the static treadmill and the speed of the treadmill was increased slowly in small increments until a comfortable walking speed, their 'preferred walking speed (PWS)' was reached. Participants were then given time to familiarize themselves with walking on the treadmill at that speed (2-3 minutes). Identical verbal instructions were given to each subject.

Each participant was then asked to walk on the treadmill under 6 conditions namely at their PWS, 25% above their PWS (High Speed) and 25% below their PWS (Low speed) each with and without the belt barrier. These conditions were randomized for each participant to minimise the likelihood of participant expectancy leading to erroneous representation of walking. Under each condition participants were given time to become comfortable with moving at that speed and then their movement was captured for 30 seconds. Participants were offered the chance to rest between each stage, although none chose to do so.

The minimum distance between the toe and the mannequin was calculated for each stride for both left and right limbs, and an average of both limbs was used as the dependent variable in the statistical analysis. Initially, a repeated measured ANOVA was carried out with within-subject factors i.e. barrier, 2 levels: with, without; speed condition, 3 levels: low, preferred, high, and a between-subject factor, group, i.e. young and older. Secondly, ANCOVA analyses were carried out on each speed condition separately. Given that older adults walked at a lower preferred speed than young adults, this had to be included in the General Linear Model as a covariate to control for this disparity.

### 4.2 Experimental Results

Preferred walking speed of the younger group (mean: 0.78 m/s, SD: 0.13) was significantly greater ($t = 2.558$, $p = 0.019$) than that of the older group (mean: 0.57 m/s, SD: 0.22). The distances from the toe to the mannequin for each group and each condition – Preferred Speed, High Speed (25% above preferred speed) and Low Speed (25% below preferred speed)) without and with the barrier are provided in Table 3. The preferred speeds on the treadmill were lower than normally encountered on fixed floors because relaxed walking speeds are naturally lower on treadmills. However, the treadmill tests allowed us to easily investigate the magnitude of contact spacing differences between the two cohorts.

The data show a statistically significant ($p=.000$) between-subject effect in distance between the toe and the 'person-shaped' object. Specifically, older adults chose to leave more space than younger adults across all conditions. The first hypothesis, i.e. that the contact buffer ($C_b$) for older adults is greater than for younger adults for a given speed, is therefore accepted. All subjects reduced this space in the presence of the barrier ($p=0.001$), with no interaction effects. This adjustment seemed to be more pronounced in the younger group than in the older group (e.g. an average adjustment of 31% for young at high speed, compared to 17.3% for older). Although not significant, this may suggest that the older group were keener to maintain their distance compared to younger group, despite pressure from behind. It is also possible that the older adults had reduced capacity to adapt to this condition compared to younger adults. In all cases the minimum distance for older adults was at least double that of young for a given condition without the barrier and around three times that of the young for a given condition with the barrier. This confirms that older adults interact differently with human-like objects in their environment compared to younger adults, during a walking task in a confined space.

| Subject Group | Toe Marker Distance for Each Condition (m) | | | | | | |
|---|---|---|---|---|---|---|---|
| | No Barrier | | | With Barrier | | | |
| | Low * Speed | Preferred* Speed | High* Speed | Low Speed | Preferred Speed | High Speed | Mean, all speeds (with barrier) |
| | Mean (s.d) | Mean *(s.d)* | Mean *(s.d)* | Mean *(s.d)* | Mean *(s.d)* | Mean *(s.d)* | |
| Young Adult | 0.125 *(0.032)* | 0.119 *(0.056)* | 0.112 *(0.080)* | 0.099 *(0.056)* | 0.068 *(0.020)* | 0.069 *(0.016)* | 0.079 |
| Older Adult | 0.282 *(0.094)* | 0.272 *(0.083)* | 0.276 *(0.104)* | 0.239 *(0.091)* | 0.245 *(0.092)* | 0.253 *(0.081)* | 0.246 |

**Preferred treadmill speed for "young adult" group = 0.78m/s, and for "Older Adult" = 0.57m/s. "Low" speed used treadmill speeds reduced by 25%, and "High" increased by 25% for each group.*

Table 3. 'Marker Distance' from toe marker to mannequin for each speed and condition

Our second hypothesis, i.e. the contact buffer would vary significantly with speed on the treadmill, was not borne out in the data (p=0.42). There was little evidence of any difference in distance between the toe and the mannequin for either the young or older subject groups with an increase or decrease in speed when no barrier was in place. When the barrier was in place, there was some evidence of an increase in mean distance with increased speed and decrease with decreased speed, but not statistically significant. The much larger variation in data range for the elderly group is also an interesting facet of the data set.

It is acknowledged that this experimental set-up was rather artificial. The treadmill was chosen for this study because of the ability to control and precisely measure speed and large numbers of gait cycles. Differences between treadmill and overground walking have been reported in the literature although it is suggested that potential differences can be minimised by providing time for the participant to familiarize themselves with the treadmill[15]. In summary, the results from the experimental study indicated that the elderly group consistently left a significantly larger distance to the mannequin than the younger group, despite moving at a lower preferred speed. Although there was no statistically significant effect for speed, this may reflect the non-natural setting and the range of speeds investigated.

We extracted the "with-barrier" marker distances from the experimental data and used them in the model as follows: 0.079m and 0.246m (for young and older groups respectively) formed the basis of the suggested average "contact buffer" distances for young and older persons of 0.034m and 0.201m in the model. Dividing these distances by treadmill speeds, they can be equated to times of 0.043s and 0.352s respectively. Although there are clear limitations of these treadmill tests, the 0.309ms differential (for older vs younger subjects) is considered appropriate as a first estimate when applying the prototype equations described in this paper. This value will be further investigated in future experimental research.

## 5. TESTING THE PROTOTYPE MODEL AGAINST REAL-WORLD EXPERIMENTS

Having developed the prototype movement adaption model, it was important to compare the model outputs, i.e. relationships between walking speed and inter-person distance, walking speed and density and flow and density, with real world experiments. One study which was considered suitable for comparison purposes, due to the presentation of detailed input and output data, was that of Cao et al[22]. Cao et al quantified pedestrian dynamics in a single file movement for crowds with different age compositions in an experimental set-up and identified clear differences in the speed and flow rates between younger and older group cohorts. The experimental set up is shown in Figure 9.

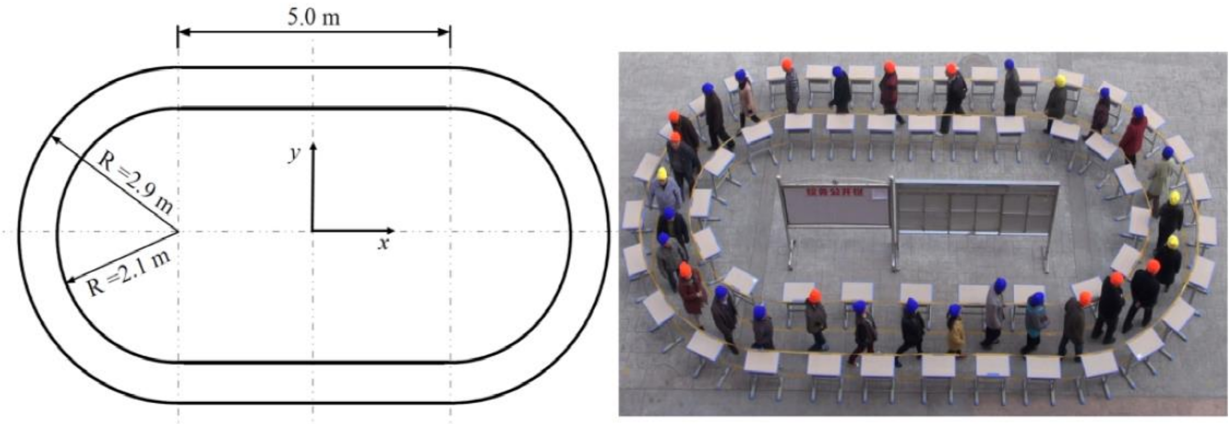



Figure 9: Experimental setup, reproduced from Cao et al[22]

The tests consisted of two cohort groups described in the study as "young" and "old". The young group consisted of 80 students aged 16-18 years old, and the old group comprised 47 older adults aged 45-73 with an average age of 52. Overall, 30 sets of experimental runs were carried out, with incrementally more subjects within the single-file circuit to increase occupant density and observe the consequential effect on walking speed. The composition of the tests was varied: 15 tests for just young, six just old and nine comprising 50% young and 50% old mixture. The results of Cao et al for young, mixed and old groups are presented in Figure 10. Note that very few data points were collected for density values above 2 people per metre for the old group in Figure 10 (c) as they became tired, and testing stopped.

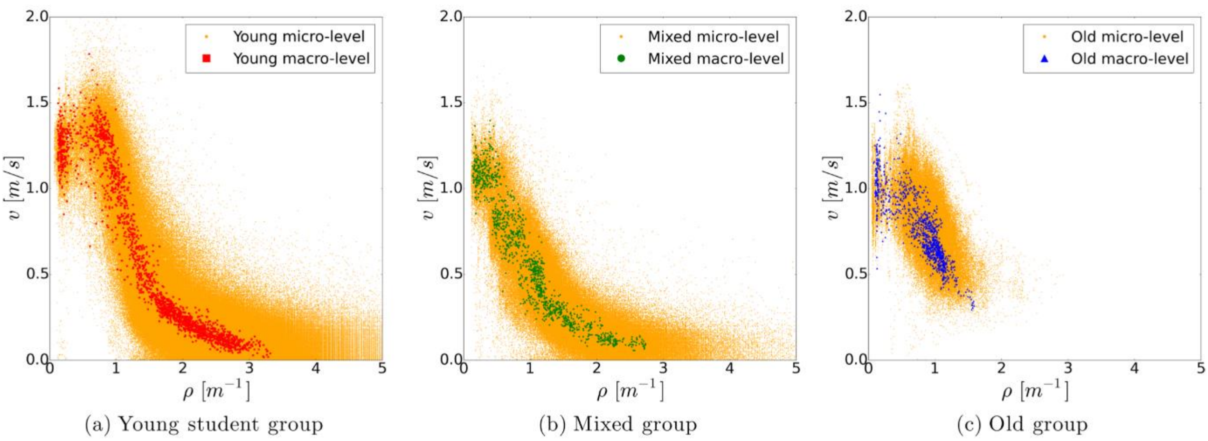



Figure 10. Scatter plot of results from the single-file tests carried out by Cao et al[22].

The scatter plots, Figure 10, show individual (per-person) instantaneous readings as 'micro-level' and values averaged across the circuit length as 'macro-level'. Note that the macro-level values are used here for comparison with the movement adaption model.

The movement adaption model was used to determine the relationship between walking speed and inter-person distance, walking speed and density and flow and density, for comparison with the Cao et al experiments. Table 4 summarises the values and indicates the sources of the parameters used in the model (Equations, 7 and 12) to characterise the young and old cohorts.

| Distance Component | Parameter | Symbol (units) | Cohort | |
|---|---|---|---|---|
| | | | Young | Old |
| Step & Foot | Height | $h$ (m) | 1.64* | 1.62* |
| | Unimpeded walking speed | $v_u$ (m/s) | 1.23* | 0.95* |
| | Contribution of step length +foot length (to determine step extent) | $A$ | 0.92^ | 0.92^ |
| | Foot length (as shoe length) | $f_l$ (m) | 0.28# | 0.28# |
| Contact buffer | Contact adaption time | $T_a$ (s) | 0.218~ | 0.548~ |
| | Maximum single-file density | $\rho_{max}$ (P/m) | 3.3* | 2.8* |

* *data from Cao et al.[22] data.*

\+ *average of male and female step length:height ratio from Hatano[24]*

^ *the average step extent at full unimpeded walking speed as derived in section 3.3 above*

\# *a representative foot (average shoe size) 250mm from Armitage[26] with allowance for 30mm for shoe heel/toe*

~ *taken as simple reaction times for ages 18 and 65 from Woods[23], with an additional 0.309 ms for older adults derived from experiments presented in section 4.0.*

Table 4: Parameters used in the model to compare with experimental results from Cao et al.[22]

The outputs of the movement adaption model are compared with Cao et al's data [22] in Figures 11, 12, and 13. Note that density in Figures 12 and 13 is calculated as the inverse of inter-person distance (participants moving in single file).

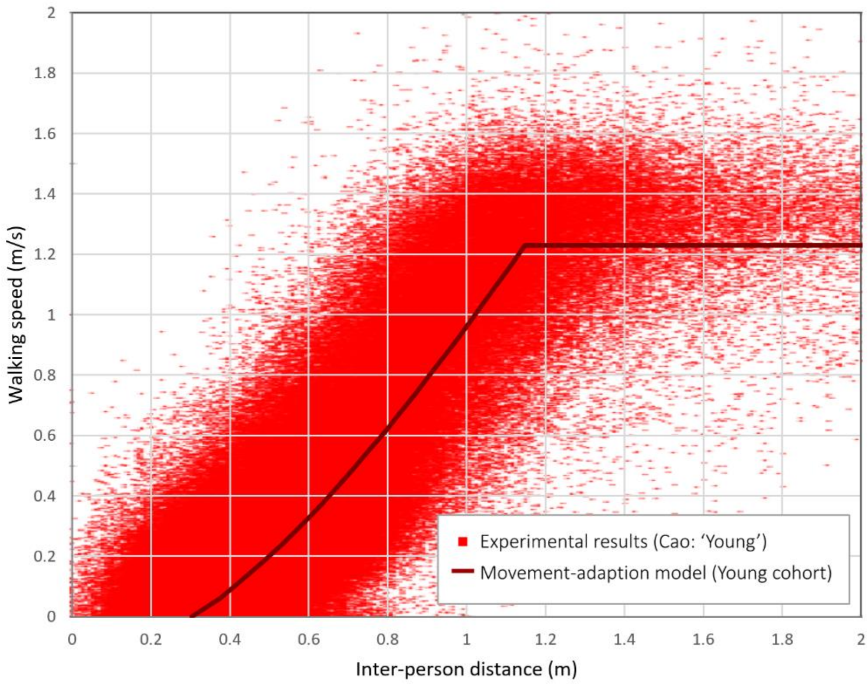



Figure 11. Comparison of experimental results Cao et al.[22] and outputs from movement adaption model for young group (walking speed v inter-person distance)

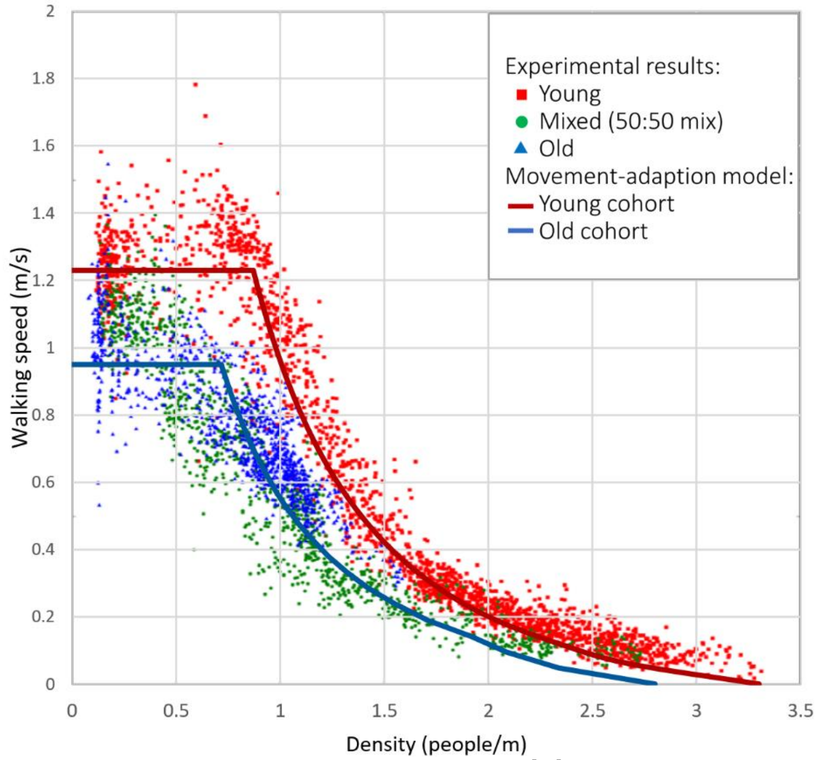


Figure 12. Comparison of experimental results from Cao et al[22] and outputs from movement adaption model for old and young groups (walking speed v density)

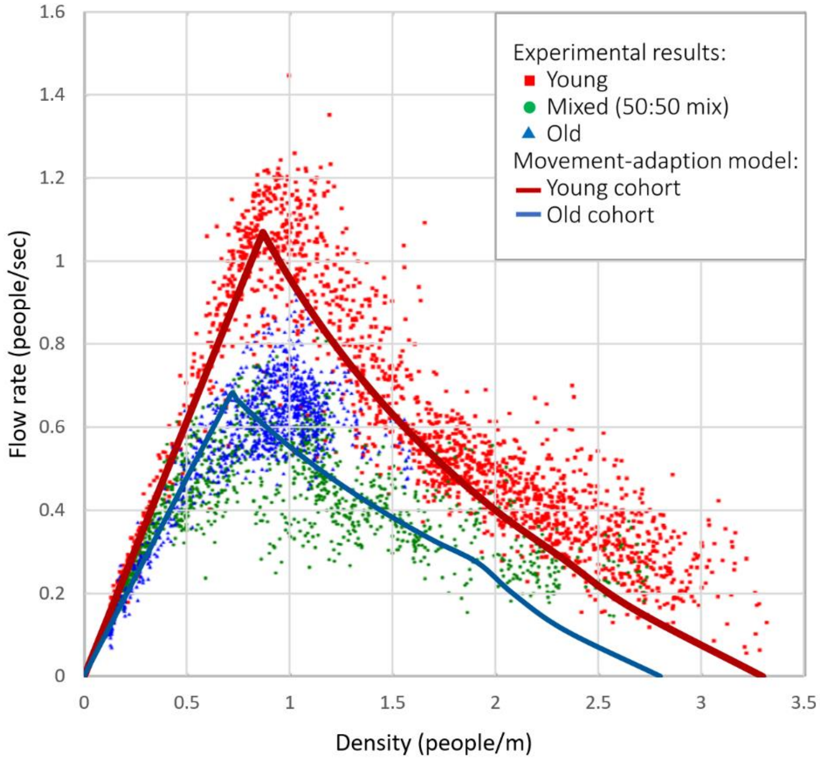


Figure 13. Comparison of experimental results from Cao et al[22] and outputs from movement adaption model (flow rate v density)

Figure 11 shows the movement adaption model outputs in terms of the relationship between walking speed and inter-person distance plotted from Equations 12a and 12b for a young student group. The plotted line for the model appears to fit well within the limits of the overall spread of the experimental data and demonstrates a reasonable alignment with the observed trends. The underlying experimental points were not published, so a deeper statistical analysis was not possible, but the right trends are observed (speed reducing with as inter-person distance reduces, below a flat-line threshold).

Figures 12 and 13 also show an encouraging correlation between the output from the movement adaption model and the experimental observations in the single-file study, with similar peak speed and flow densities approximately in centre of the scatter of experimental data for the "young" group. The "old" cohort shows a similar pattern, although peaking slightly before the experimental data for the flow rate in this case. Although a 'mixed' cohort group is not plotted for the model (because it would require a computer simulation model to replicate the 1:1 ratio mixing of the two demographics) the mix of young and old produces walking speeds and flow rates which are very similar to the 100% old group. This indicates that the elderly subjects completely dictated the overall flow, which reflects that a group in a closed single-file circuit will inevitably move at the rate of the slowest member in a congested situation. The implication of this is important to note, i.e. that in sufficient proportion, in a moderately constrained situation, the lower-ability group dictates the overall flow.

## 6. DISCUSSION AND CONCLUSION

A new predictive model for crowd flow analysis, based on pedestrian biomechanics and anthropometric data, was presented in this paper. The proposed model, called the movement adaption model, uses (a) the physical space occupied by each pedestrian's body as part of the physical walking process and (b) the spatial buffer left between points of potential contact with other pedestrians, to predict speed and movement at different levels of congestion. It differs from most other models because the crowd flow and speed/density relationships emerge from the biomechanical movement of individuals and their adaption to positions and potential contact with others, whereas common modelling approaches use pre-established speed/density relationships as required calibration inputs instead. The movement adaption model, when fully developed and validated, should enable predictive modelling of any mix of population groups in terms of age, body size, culture etc. when implemented as a computer model, using demographics data as inputs (height, foot size, response/adaption time etc.). This is not possible with models which require recalibration for each new population group.

We derived values for use in the model from existing literature and our own experimental data. As a first step we used the model to compare the movement of young and older populations and investigated the differences in inter-person distance observed by young and older adults when walking, using a controlled, treadmill-based laboratory set-up. These experiments were useful as they confirmed that older adults do behave differently from young adults in terms of interacting with an object (representing a potentially obstructing person) ahead of them while walking. The data provided us with an empirically derived order of magnitude for this difference. The experiment yielded the following outcomes:

a. Older adults maintained a significantly greater distance from the mannequin compared to the young adults, despite having a significantly lower preferred speed and had a wider variation across the group demographic. This variation should be reflected in any subsequent computer simulation approaches which may use these equations.

b. The feeling of perceived congestion (with the addition of a belt barrier) did produce significant reductions in distance to a simulated person in front for both younger and older age groups, although it was more pronounced in the older group. This is despite the experimentally induced "congestion" not physically hampering the gait mechanics. This suggests perhaps that in a crowded situation older people are more likely to maintain their position despite perceived pressure from behind. This may be due to reduced adaptive capacity of older adults during locomotion.

It is unknown exactly how the reduced adaptive capacity of older adults may determine the contact buffer. We hypothesise that the contact buffer is derived from the simple reaction time plus a further adaption time required to adjust for and execute an appropriate movement strategy for a given crowd situation. However, further research is required to unpick this phenomenon across a range of ages and crowd complexities. We have implemented the proposed movement adaption model to produce results for inter-person distance and density in young and old pedestrian movement that are comparable to the experimental results reported by Cao et al[22]. It is important to note that, at this stage, several assumptions and approximations have necessarily been made with regard to the model parameters which have not been adjusted or calibrated in any way. It was not the purpose of this paper to calibrate this initial model, but rather to introduce the concepts and run some preliminary tests that would inform future experiments. In particular, we attempted to avoid an analytical form of mathematical modelling which required extensive calibration but instead built on a combination of experimentally validated biomechanical and cognitive components which reflect the demographics of the "people" being quantified, wherever possible.

## 7. FURTHER WORK

While the fundamental approach taken for the movement adaption model bears encouraging comparison with one set of experiments, these were well controlled, single-file tests with a well quantified set of group cohorts in controlled experimental conditions in one country. The intention is to further develop the understanding of the core components at play for wider population sets, in different conditions and potentially different geometric situations. This new movement adaption model is sensitive to both the contact adaption time and the step extent, thus both factors should be the focus of future experiments for larger population sample sizes with respect to age, body size and levels of evacuation stress. The potential effects of asynchronous stepping motion, and "overlapping" steps should also be experimentally investigated.

The proposed model does not yet include assessments of body sway, altered stride cadence, or wider variations in body volumes and walking speeds which should be considered for movement in wider 2D planes. The interrelationships between other important factors such as personal space, i.e. the area surrounding an individual that is perceived as private and into which movement by another is considered intrusive, and social connections also may be explored. As the model develops, computer simulation will be required to analyse these complex interrelationships and to analyse the combined effects of e.g. obesity and variability of speed within age groups. These will be addressed as the level of sophistication of the model is increased with further experimental investigation. The implementation of a validated model which can accurately assess the biomechanics and cognitive responses of wider set of crowd member demographics will be crucial if we are to understand the impact of the predicted demographic change on flow dynamics and ultimately the safety of building occupants. The ongoing strategy is specifically not to 'calibrate' the model, but to further develop a fundamental understanding of the underlying mechanisms which, when combined together should display realistic speeds and flow rates. This approach differs from existing models because we use any disparity with "real world" results as an indicator that the model form or parameters need further study and not calibration to fit the desired result.

## ACKNOWLEDGEMENTS

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Tables:

| | | | |
|---|---|---|---|
| Age | Emotional state | Health status | Step frequency |
| Body projected area | Fatigue | Height | Step length |
| Bottlenecks, openings | Fitness | Lateral sway | Vision |
| Culture | Gender | Personal space | Weight |
| Occupant density | Group parameters | Social relations | Environment |
| Emergency or non-emergency | *Headway | Stair gradient | |

**Note: "headway" is often also referred to elsewhere as "inter-person distance".*

Table 1: Primary parameters for crowd flow identified in the scoping review

| Group | Male no. | Female no. | Age | | Height (cm) | | Leg Length (cm) | | Weight (kg) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Min-Max | Mean *(s.d.)* | Min-Max | Mean *(s.d.)* | Min-Max | Mean *(s.d.)* | Min-Max | Mean *(s.d.)* |
| Young Adult | 4 | 5 | 19 - 34 | 24.44 *(4.42)* | 166 - 186 | 171.33 *(12.12)* | 81 - 99 | 88.33 *(5.63)* | 61.9 - 100.0 | 77.34 *(14.25)* |
| Older Adult | 6 | 7 | 60 - 84 | 67.77 *(8.62)* | 152 - 178 | 167.15 *(7.83)* | 79 - 97 | 88.33 *(5.63)* | 59.9 - 104.1 | 77.43 *(11.40)* |

Table 2. Demographic data for laboratory study

| Subject Group | Toe Marker Distance for Each Condition (m) | | | | | | |
|---|---|---|---|---|---|---|---|
| | No Barrier | | | With Barrier | | | |
| | Low * Speed | Preferred* Speed | High* Speed | Low Speed | Preferred Speed | High Speed | Mean, all speeds (with barrier) |
| | Mean (s.d) | Mean *(s.d)* | Mean *(s.d)* | Mean *(s.d)* | Mean *(s.d)* | Mean *(s.d)* | |
| Young Adult | 0.125 *(0.032)* | 0.119 *(0.056)* | 0.112 *(0.080)* | 0.099 *(0.056)* | 0.068 *(0.020)* | 0.069 *(0.016)* | 0.079 |
| Older Adult | 0.282 *(0.094)* | 0.272 *(0.083)* | 0.276 *(0.104)* | 0.239 *(0.091)* | 0.245 *(0.092)* | 0.253 *(0.081)* | 0.246 |

**Preferred treadmill speed for "young adult" group = 0.78m/s, and for "Older Adult" = 0.57m/s. "Low" speed used treadmill speeds reduced by 25%, and "High" increased by 25% for each group.*

Table 3. 'Marker Distance' from toe marker to mannequin for each speed and condition

| Distance Component | Parameter | Symbol (units) | Cohort | |
|---|---|---|---|---|
| | | | Young | Old |
| Step & Foot | Height | $h$ (m) | 1.64* | 1.62* |
| | Unimpeded walking speed | $v_u$ (m/s) | 1.23* | 0.95* |
| | Contribution of step length +foot length (to determine step extent) | $A$ | 0.92^ | 0.92^ |
| | Foot length (as shoe length) | fl (m) | 0.28# | 0.28# |
| Contact buffer | Contact adaption time | $T_a$ (s) | 0.218~ | 0.548~ |
| | Maximum single-file density | $\rho_{max}$ (P/m) | 3.3* | 2.8* |

* *data from Cao et al.[22] data.*
\+ *average of male and female step length:height ratio from Hatano[24]*
^ *the average step extent at full unimpeded walking speed as derived in section 3.3 above*
\# *a representative foot (average shoe size) 250mm from Armitage[26] with allowance for 30mm for shoe heel/toe*
~ *taken as simple reaction times for ages 18 and 65 from Woods[23], with an additional 0.309 ms for older adults derived from experiments presented in section 4.0.*

Table 4: Parameters used in the model to compare with experimental results from Cao et al.[22]